Medical Adhesives and Skin Adhesion

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Abstract:

Medical adhesives are widely used in hospitals to secure medical dressings, life support equipments, and monitoring devices onto skin, which requires careful consideration and knowledge about skin and adhesives. In this paper, the medical applications will be overviewed, followed by a discussion of skin characteristics, principles of adhesion, challenges for skin adhesion, and commercially available skin adhesives.

Introduction:

Medical Pressure Sensitive Products (MPSP) are important in the medical device industry and are extensively used in hospitals. Those medical products include adhesive transfer tapes, single side coated products, and double side coated tapes. Adhesive transfer tapes and double coated tapes are usually used by Medical Device OEMs to adhere medical devices, strips, and pouches for medical diagnosis and management of waste discharges. Single side coated products serve as bandages, medical tapes, wound dressings, surgical drapes, wound closure tapes, and skin attachments for electrodes, IV dressings, and medical sensors. Fueled by population demographics, product innovation, and increased market needs within and outside the United States, the global market of Medical Pressure Sensitive Products has grown from $1.5 billion in 2000 to $2.5 billion in 2010, and is projected to be $3.5 billion in 2015 [(1)].

The focus of the development of MPSP is primarily directed towards customer oriented requirements such as skin adhesion, biocompatibility, and permeability for water vapor, and air, which requires deep understanding of adhesion science and skin characteristics.

Skin Characteristics:

Skin is the largest organ in the body averaging 3000 square inches and 7 pounds in an adult, which provides primary function as a two-way barrier between the body and environment. On one side, skin prevents inward penetration of destructive chemicals, infective microorganisms, and damaging radiation from sun. On the other side, skin prevents outward passage of water and electrolytes. Such barrier function of the skin is largely situated in the epidermis, as illustrated in the Figure 1.

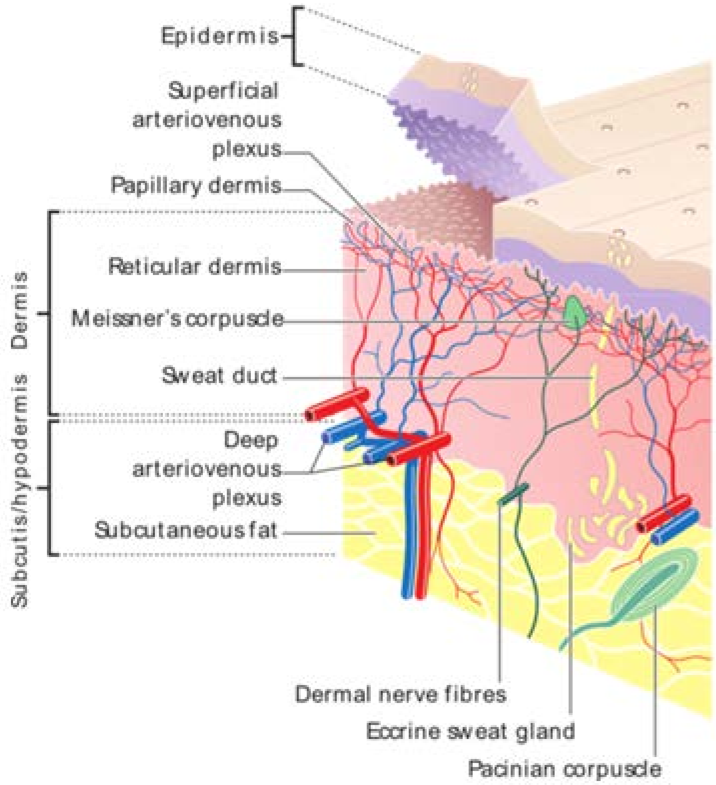

Figure 1. Illustration of Skin Construction (2)

Skin, mostly in the layer of hypodermis, also contains nerves and sensatory receptors, which detect incoming stimuli of touch, vibration, pressure, temperature, pain, and itch.

The characteristics of skin composition, construction, and function make the adhesion to skin very challenging, For example:

1. Skin is a self renewable and replenishable surface:
   The outermost surface of epidermis, called stratum corneum, is made of cells migrated from the base of epidermis and is sloughed off in about 14 days, while the entire epidermis renews itself on a cycle of 45 ~ 75 days (3). Therefore a medical pressure sensitive adhesive must stick to the layer that is being shed.
2. Skin is a contaminated surface with water, oil, salt, lotion, cream, and loose debris:
   A medical pressure sensitive adhesive must be tolerant to variety surface contaminates in order to stick to the skin layer.
3. Skin is a low surface energy (LSE) surface:
   Being composed of lipidic components, especially the sebums, skin surface is primarily hydrophobic and has low surface tension of 25~29 dyne/cm (4). Therefore a medical pressure sensitive adhesive must have equivalent or lower surface tension to achieve sufficient skin wet out and ultimate skin adhesion (Table 1).

Material	Surface Tension (dyne/cm)
PTFE	18
Silicone	21
Skin	25~29
PP / PE	31
Acrylic	38
Water	72

Table 1. Skin as Low Energy Surface

4. Skin is a rough surface with hair, folds, crevasses, pores for sweat and oil glands, and wrinkles:
   For example, the mean depth of skin crevasses (measured by profilometry) is 91 micron for an old man and 36 micron for a young man [(5)]. Therefore a medical pressure sensitive adhesive must be soft enough and be able to flow to achieve ultimate skin adhesion.
5. Skin is an elastic surface:
   The mechanical properties of skin depends mainly on the dermis, which is elastic to a degree and can be stretched reversibly by 10~50%. Therefore a medical pressure sensitive adhesive must have resistance to constant elastic stretch to achieve robust skin adhesion.
6. Skin is a sensitive live surface:
   Being a live surface, skin is highly sensitive and prone to allergic reaction when in contact with certain substance (allergen) that the immune system believes is dangerous and reacts to it. The longer the skin is in contact with the allergen, or the stronger the allergen is, the more severe the skin allergic reaction will be.
7. Skin is a highly variable surface in its physical constructions and properties described above:
   Skin is highly variable with gender, age, ethnicity, location on the body, and ambient conditions. For example, one of the skin barrier properties against water loss is referred as TransEpidermal Water Loss (TEWL). A typical value of TEWL for a intact skin of a forearm is 9.7 g/m^2/h in contrast to a typical value of intact skin of a palm is 101.4 g/m^2/h. In another example the tensile strength of human stratum corneum could change from 3 MPa at 100% relative humidity to 370 Mpa at 30% relative humidity [(6)], as illustrated in Figure 2.

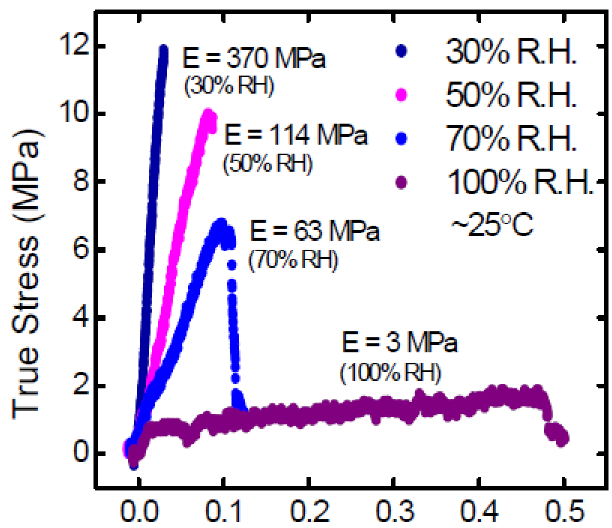

Figure 2. Stress-strain data for 20 micron thick free standing films of human stratum corneum

As a consequence of those skin characteristics, there would be an upper limit on how much skin adhesion can be achieved, since surface contact is limited and failure of the adhesion bond occurs mostly in the stratum corneum.

Principle of Skin Adhesion:

Pressure Sensitive Adhesives (PSA) are viscoelastic materials that can adhere to surfaces upon application of light contact pressure and leave no residue when they are removed. The viscoelastic property of PSA controls its adhesion to the substrate surface and determines the duration of its application. Such viscoelatic behavior of a PSA can be measured by a dynamic mechanical analyzer (DMA) with storage (elastic) modulus (G') and loss (viscous) modulus (G"), where the elastic modulus describes the solid-like character of the PSA and the loss modulus describes the liquid-like character of the PSA. Tack (the ability of quick adhesion under light pressure) is a low rate process where the adhesive should be liquid like. To be self tacky, an adhesive has to have storage modulus lower than $3x10^5$ Pa so that is able to flow sufficiently to promote intimate contact on the substrate (Dahlquist criteria). Peel adhesion (the ability to resist its removal by peeling) is the high rate process where the adhesive should be solid-like and influenced by modulus below glass transition temperature (Tg), so that higher force can be obtained to deform the adhesive. Shear resistance is the low rate process at high deformation (cohesive strength) and is influenced by the plateau modulus at high temperature.

Many conventional low modulus polymers are flexible enough and have low glass transition temperatures (Table 2) so that can be formulated as pressure sensitive adhesives.

Polymer	Glass Transition Temperature (°C)
Silicone	-90
Polybutadiene	-85
Natural Rubber	-73
Polyethylhexylacrylate	-70
Polyurethane (polyether polyol/MDI)	-30
SIS	-28

Table 2 Glass Transition Temperature of Various Polymers

To formulate a medical pressure sensitive product a multitude of customer needs have to be met. Compatible to skin, robust skin adhesion, breathable to air and moisture, and kind removal without skin trauma are of primary importance.

The first customer requirement to consider for medical pressure sensitive adhesives is of course the skin compatibility. No adhesive is acceptable if it is not compatible with skin, or induces skin reaction, or causes toxicity. Skin sensitivity can be measured on animals through either Primary Skin Irritation (PSI) test or Repeat Patch Insult (RPI) test. Cytotoxicity is usually determined by extraction of water soluble components and dermal injection into rabbits or systematic injection into mice.

Skin, being a replenishable, LSE, contaminated, rough, elastic, and highly variable surface, is very difficult to bond or to adhere to. To achieve robust adhesion on skin, the medical pressure sensitive adhesive typically has low polarity, has low surface energy, is flowable at body temperature, and is cohesively strong, which are impacted by the chemical composition and structure of the PSA base polymer. Generally speaking, higher MW between crosslinks, lower percentage of polar comonomers, and linear chain backbone without side chains usually result in a more flexible and flowable PSA and thus tend to exhibit higher tack and stable adhesion (less adhesion build up).

Another way to reduce the stiffness (modulus) or increase flexibility of the adhesive is to use tackifier resin. When a tackifier is homogeneously mixed in the adhesive, the tackified adhesive would have lower modulus and higher glass transition temperature, as illustrated in Figure 3.

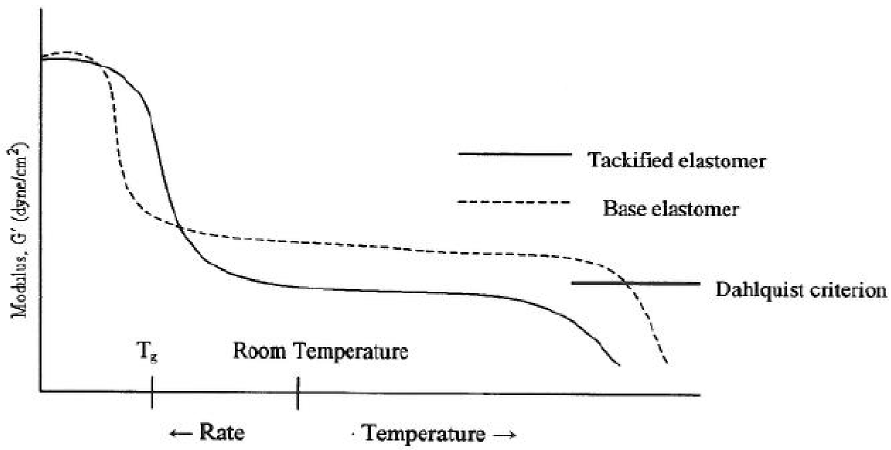

Figure 3. Dynamic Mechanical Spectrum of a PSA in the Tackified and Non-tackified States [7]

For a PSA to stick to skin, the surface energy of the adhesive should be lower than the surface energy of skin, which is about 25 ~ 29 dyne/cm (even lower than the surface energy of polyethylene, see Table 1). Although having lower surface energy is only a prerequisite for a PSA to wet out surface and to achieve ultimate adhesion, this feature further requires lower polarity for the skin adhesive. The adhesive polarity has to be counter balanced with its cohesive strength or low adhesive residues on skin upon removal.

Medical pressure sensitive adhesives also need high breathability to air and moisture. Silicone polymer has inherent high permeability to oxygen and carbon dioxide (a few hundred times better than most conventional organic polymers), which is one of the advantages to use silicone adhesive for medical applications. To improve breathability of hydrocarbon adhesives, thinner or discontinuous (porous) adhesive coatings are usually used, which also improves moisture vapor transmission rate (MVTR) as shown in Figure 5.

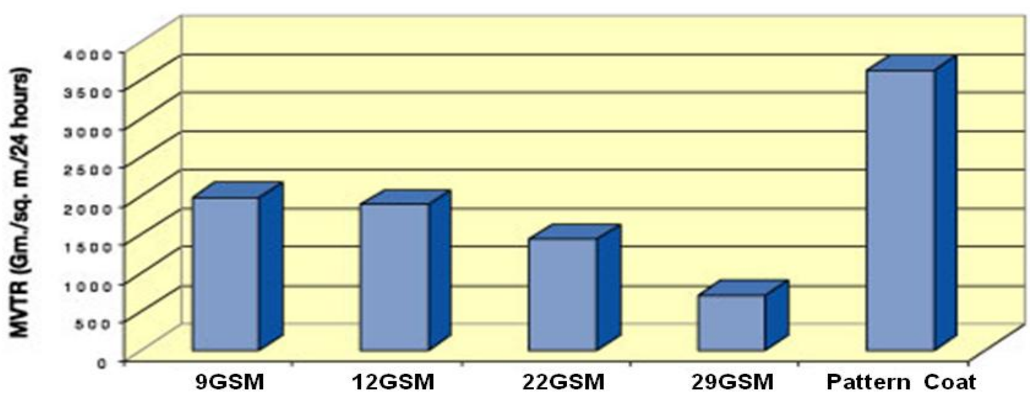

Figure 4. MVTR Performance over Adhesive Coating Weight and Coating Pattern [8]

Having robust skin adhesion and reliable bonding securement is essential for being a good skin adhesive. Another important aspect is the ability to kindly remove the adhesive from skin without causing significant skin trauma and pain. Peeling off medical pressure sensitive product away will stretch the skin (being of elastic surface) and could potentially cause “skin stripping” or skin trauma, especially when the interfacial bonding at adhesive / skin interface is stronger than the cohesive strength of stratum corneum layer. Since the cohesive strength of stratum corneum layer decreases significantly at higher humidity as shown in Figure 2, keeping the skin relatively dry would maintain the high cohesive strength of the skin and could thus reduce the tendency of skin stripping, especially stripping off as large “cell clusters”. Interfacial bonding at adhesive / skin interface is obviously determined by the type of adhesives used. Silicone medical adhesive, comparing to other hydrocarbon adhesives, has shown to have low interfacial bonding and thus low skin trauma but high flowability and thus stable skin adhesion through mechanical interlock in skin pores, as shown in Figure 5.

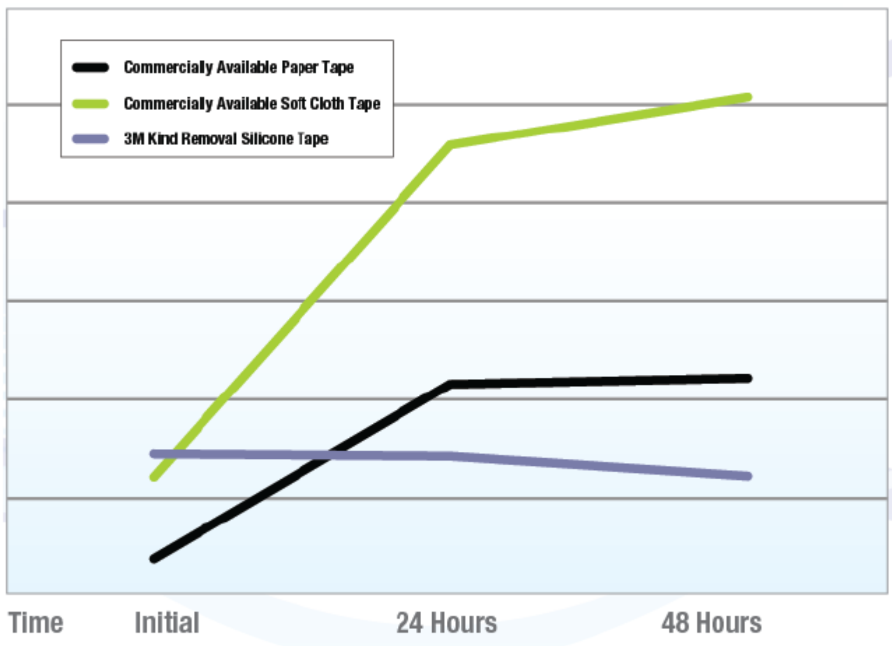

Figure 5. Skin Adhesion Stability

The comparison of skin stripping and skin trauma between silicone adhesive and hydrocarbon adhesive is illustrated in Figure 6.

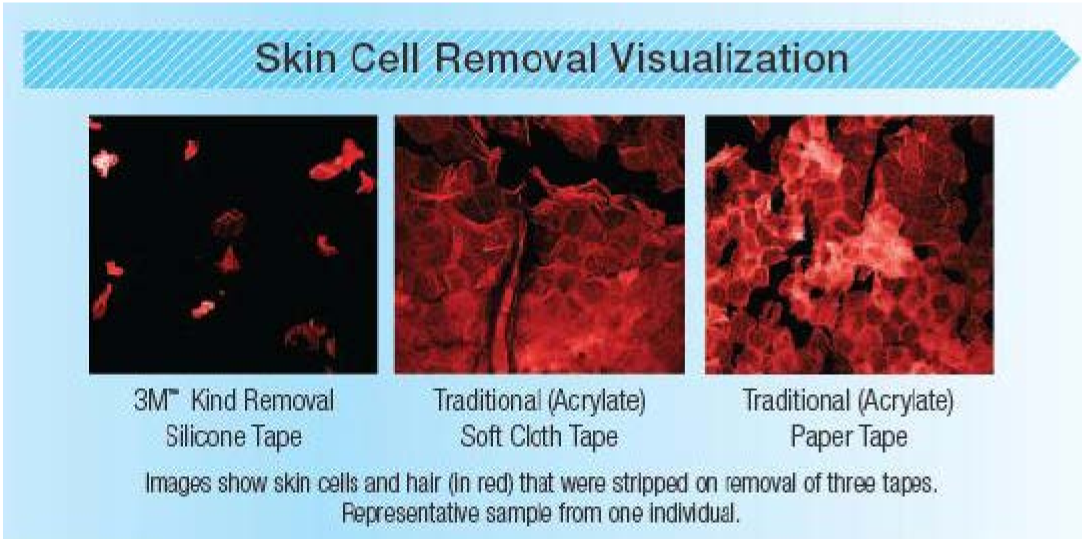

Figure 6. Confocal Microscope Images of Skin Cells on Adhesive Surfaces

When occurred, skin stripping upon adhesive removal would damage the skin barrier, which could further result in additional water loss, measured by higher TEWL as shown in Figure 7. Patients who suffer from skin trauma upon adhesive removal not only experience discomfort but they often require more nursing time, more materials, may take longer to heal, and may have increased risk of infection and chronic wounds.

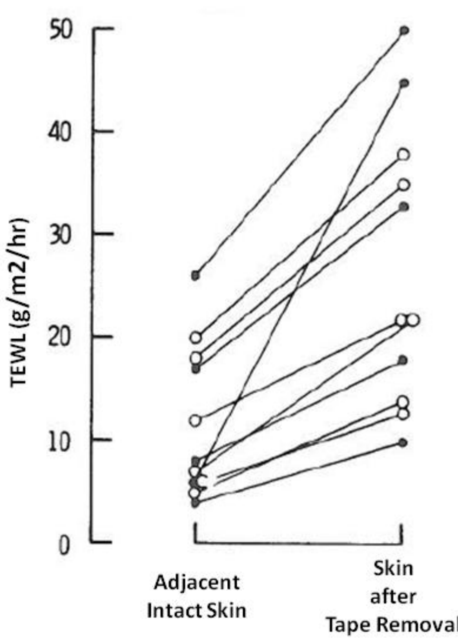

Figure 7. TEWL Comparison between Intact Skin and Skin after Tape Removal

for a Premature Infant [9]

On the other side, skin stripping would leave stripped-off skin cells on adhesive surface, which would contaminate the adhesive surface, detackify the adhesive, and therefore interfere with the “rewetting” or “restick” property of the adhesive. This restickability or repositionability is another preferred customer feature which would enable medical pressure sensitive product to be reapplied. However such property is generally not built into medical adhesives partially because most of medical adhesives would strip off skin cells when removed off from skin even within seconds after its initial contact with skin. Silicone adhesive offers good adhesive repositionability due to its low trauma characteristics.

Medical Adhesives:

Acrylic adhesives are the most common medical adhesives, which can be tailor made for specific medical applications. Typically a medical acrylic adhesive contains both high Tg monomers (for better cohesive strength) and low Tg monomers (for better tack and surface wet-out) and does not typically require tackifiers for pressure sensitive properties. .

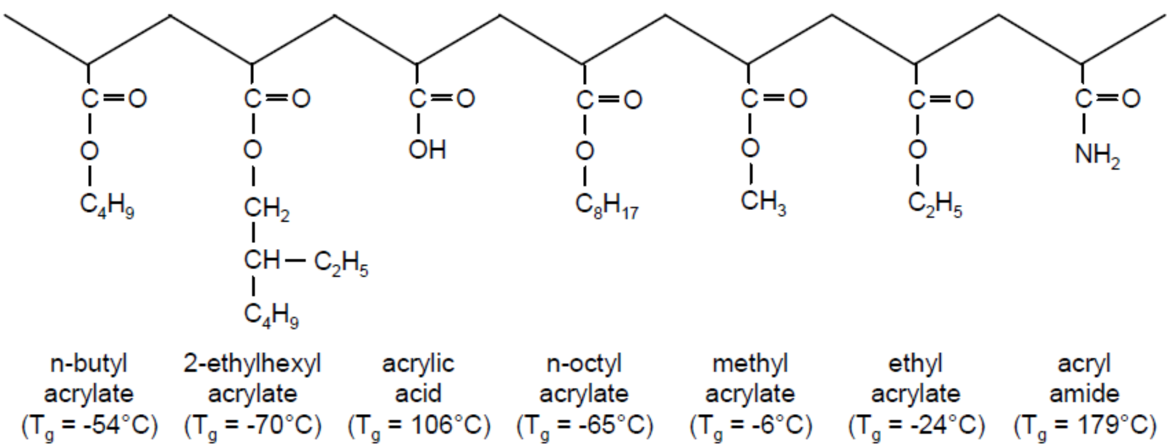

Figure 8. Typical Acrylic PSA Co-monomers

High Tg acrylic monomers are polar in nature and tend to increase the surface energy and the “hardness” of the adhesive system. Generally speaking, acrylics are “harder” than rubber based adhesives. This can be seen in a less aggressive tack and slower adhesion build-up. Having lower contents of high Tg monomers in the acrylic adhesive would reduce the “hardness” and thus enhance skin adhesion.

Medical silicone adhesives are typically compounded from silicone elastomers and MQ tackifier resins. Their major benefits are hypoallergenic, nontoxic, non-polar, robust skin adhesion, highly breathable to air, and low skin stripping upon removal. The major drawbacks are cost and the fact that they are generally applied via solvent coatings. They are widely used in the transdermal drug delivery systems and are emerging as low trauma skin adhesives.

Polyisobutylenes (PIBs) are also used as medical pressure sensitive adhesives, especially as the hydrophobic polymer matrix for medical hydrocolloid adhesives. A typical hydrocolloid adhesive contains polyisobutylene as well as water absorbing additives, such as carboxymethyl cellulose (CMC). The resulting multi-phase hydrocolloid structure allows capability of absorbing fluids without losing its adhesion, so that hydrocolloid adhesives are widely used as wound dressing to manage wound exudates.

The typical properties of common classes of medical pressure sensitive adhesives can be further compared and summarized for the general performance such as the information found in Table 3.

Property	Acrylic	Nature Rubber	Synthetic Rubber	Polyolefin	Polyurethane	Silicone
Tack	low to high	high	high	medium	low	low to high
Peel Adhesion	medium to high	high	high	medium	low to medium	medium
Cohesive Strength	low to high	high	high	low	low to medium	high
Adhesion Stability upon Aging	poor	poor	poor	medium	medium	excellent
Plasticizer Resistance	low to medium	low	low	low	medium	good
Oxidation Resistance	good	poor	poor	poor	good	excellent
Adhesive Color	clear	yellow	clear to straw	clear to straw	clear to straw	clear
Solvent Resistance	high	fair	fair	fair	high	excellent
Permeability to Air	poor	poor	poor	poor	poor	excellent
MVTR	good	poor	poor	poor	good	fair
Repositionability on Skin	poor	poor	poor	poor	fair	excellent
low Skin Sensitivity	good	poor	good	good	good	excellent
Low Skin Trauma	poor	poor	poor	good	good	excellent
Cost	medium	low	low	medium	high	high

Table 3. Typical Properties of Common Classes of Medical Adhesives

Summary:

As demand for medical devices that are more patient friendly continue to expand, the medical adhesives become part of improving customer experiences. The development of medical adhesives will continue to grow, which will further requires better understanding of skin science, adhesion science, material science, and customer requirements.

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